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DEFORMED SHAPE ANALYSIS OF COUPLED GLAZING SYSTEMS

Ryan Alberson and Carrie Davis
Protection Engineering Consultants
14144 Trautwein Road
Austin, TX 78737

Kirk Marchand
Protection Engineering Consultants
4203 Gardendale, Suite C112
San Antonio, TX

Ed Conrath
Protection Engineering Consultants
Omaha, NE

Samuel Misko
Jacobs Technology
1020 Titan Court
Fort Walton Beach, FL 32547

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Ryan Alberson*, Carrie Davis*, Kirk Marchand^, Ed Conrath%, Samuel Misko#

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*Protection Engineering Consultants, Austin, Texas; ^San Antonio, Texas; %Omaha, Nebraska
#Jacobs Technology, Fort Walton Beach, Florida

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139 Barnes Drive, Suite 1
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14. ABSTRACT
Glazing in storefront and curtain wall configurations is increasingly used in areas subjected to blast load. Current design approaches typically use single-degree-of-freedom (SDOF) methods to analyze the performance of both the glazing and mullions. The flexural resistance and mass of each component must be identified to solve the SDOF. The resistance is calculated based on span, support conditions, cross sectional stiffness and an assumed deformed shape. Dynamic verification of deformed shape is difficult to assess through testing and has historically been calculated through analytical and numerical methods. However, new measurement methods provide high resolution, high speed deformation measurements through the use of Digital Image Correlation (DIC), which is a stereoscopic, high speed camera setup capable of measuring the strain and deflection of both the glazing and mullions simultaneously in three dimensions.

Protection Engineering Consultants (PEC) conducted a shock tube test series and two blast tests using DIC to measure glazing and mullion deformation for high strength glass. DIC data from the shock tube tests was used to determine the deformed shape and corresponding strain (and stress) states of the glass to improve the resistance curve used in the SDOF model. In the blast tests, the windows were installed in a storefront configuration and DIC was used to measure the deformation of the glazing and the mullions simultaneously such that effects from the coupled movements of the windows and mullions could be assessed. The validated SDOF models of the glazing and mullions were used to compare coupled versus uncoupled analysis to identify potential improvements. Coupled analysis has the potential to create significant material and connection efficiencies in design to resist blast loads.

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Deformed Shape Analysis of Coupled Glazing Systems

Ryan Alberson, Protection Engineering Consultants, Austin, Texas, USA
Carrie Davis, Protection Engineering Consultants, Austin, Texas, USA
Kirk Marchand, Protection Engineering Consultants, San Antonio, Texas, USA
Ed Conrath, Protection Engineering Consultants, Omaha, Nebraska, USA
Samuel Misko, Jacobs Technology, Tyndall Air Force Base, Florida, USA

ABSTRACT

Glazing in storefront and curtain wall configurations is increasingly used in areas subjected to blast load. Current design approaches typically use single-degree-of-freedom (SDOF) methods to analyze the performance of both the glazing and mullions. The flexural resistance and mass of each component must be identified to solve the SDOF. The resistance is calculated based on span, support conditions, cross sectional stiffness and an assumed deformed shape. Dynamic verification of deformed shape is difficult to assess through testing and has historically been calculated through analytical and numerical methods. However, new measurement methods provide high resolution, high speed deformation measurements through the use of Digital Image Correlation (DIC), which is a stereoscopic, high speed camera setup capable of measuring the strain and deflection of both the glazing and mullions simultaneously in three dimensions.

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INTRODUCTION

PEC led a team consisting of PPG Industries, Physical Security LLC and The US Air Force Research Laboratory (AFRL) at Tyndall AFB, Florida in the performance of a Defense Acquisition Challenge (DAC) project to evaluate Herculite® XP high strength glass for use in commercial glazing systems to protect Department of Defense (DoD) personnel in blast overload situations. Herculite® XP is a PPG Industries glass product with roughly twice the residual stress as typical fully tempered (FT) glass. The research program included quasi-static tests of high-strength glass at PEC, shock tube tests of punched windows (insulating glass units (IGUs) with commercial window frames) at ABS Consulting (ABS), and a full-scale blast test at AFRL on IGUs in punched window and storefront configurations using commercially available framing systems. The goal of the DAC project was to demonstrate the effectiveness and efficiency of high strength glass in protective applications. This research also provided data to confirm parameters for use in fast running design tools, to develop a robust and conservative design method for specifying high-strength glass, and to evaluate human injury due to high-strength glass.

This paper focuses on the deformed shape of the mullions and glazing observed during dynamic testing and the implications for coupled analysis. Response of the glass and mullions was measured using 3D digital image correlation (DIC) with high speed cameras in place of traditional deflection gauges. DIC can make thousands of measurements over the entire visible area of the system thereby providing higher accuracy and frequency for required data than is possible and/or practical with traditional deflection gauges. This measurement technique uniquely facilitates detailed analysis of the deformed shape of the glazing and mullions and their interaction. Deformed shape is typically assumed to be parabolic for glazing and mullions, but this is not strictly true over the time history of response. DIC can also be used to further develop multi-degree-of-freedom (MDOF) or finite element analysis (FEA) models for coupled glazing and mullion system response that incorporate information learned from the deformed shape analysis.

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2D and 3D DIC has been used in a number of industries for at least the past 10 years mainly for the measurement and depiction of strain fields as they develop in material specimens or structural components undergoing static testing. The accuracy and reliability of 3D DIC measurements are dependent solely on the quality of the images captured by the stereoscopically mounted cameras. With the recent development of reasonably priced, high speed, high resolution digital cameras (2-4M pixels) over the past 3-5 years, the number of potential applications of this technology has also grown to include dynamic testing. AFRL's Engineering Mechanics and Explosive Effects Research Group (EMEERG) has since developed specialized implementation techniques that now allow for accurate and reliable 3D DIC measurements in laboratory and full scale air blast environments.

INSTRUMENTATION SELECTION

Due to the light weight and relatively fragile nature of the windows and IGUs it was decided that only non-contact measurement solutions should be considered for use in measuring the response during dynamic testing. This effectively eliminates the possibility of any localized failures or influence of the response from traditional contact measurement techniques. For dynamic testing using shock tube or full scale arena blast testing, there were only two measurement techniques considered: high speed time-of-flight laser range finders (LRF) and DIC. Laser range finders can be used in these types of environments with limited success if correctly positioned and deployed with an appropriate target material. These types of gauges, however, can only obtain a single 1D measurement per gauge from a fixed point that is determined by the position and alignment of the gauge. DIC uses two high speed cameras to measure thousands of 3D points that are spatially defined by their coordinates on the surface of the specimen.

DIC can be used to track areas of interest, thereby providing thousands of strain and 3D displacement measurements; or to track discrete targets, which provides a single 3D displacement measurement at each point. The areas of interest must be covered by a high contrast random pattern and the targets must be designated by high contrast quadrature target or a large outlined dot. The material used to apply these patterns/targets was selected so as to effectively eliminate any effect the material could have on the strength or response of the specimen.

TEST SETUP

Shock Tube Testing

PEC performed 21 shock tube tests at the ABS facility in Bulverde, Texas on high-strength windows in steel or aluminum frames. The nominal glass size was 3-ft × 5-ft (0.91 m × 1.52 m). The main test variables were window layup, frame type, and load. Loads on the windows were varied so as to cause two types of response: "no break" and "just cracked" glass hazard conditions. In addition, some identical tests were performed to evaluate repeatability. Two types of windows were tested: monolithic lites and IGU layups. The single lites used monolithic glass in a steel frame (nested angles secured to the glass with glazing tape and anchored on all sides). IGUs consisted of a monolithic outer pane and either monolithic or laminated inner pane (side away from threat or facing out of the shock tube). The IGU window frames were anchored along the jambs only (the head and sill spanned horizontally). ABS was able to reach peak pressures near 30 psi (0.21 MPa) and peak impulses near 300 psi-ms (2.1 MPa-ms).

Instrumentation used during the shock tube tests included pressure gauges to measure load, two Banner time-of-flight laser range finders and/or digital image correlation (DIC) to measure response, and high-speed video cameras to document the test. Two Phantom V7.3 high-speed cameras, operating at full resolution of 800x600 and at a frame rate of approximately 6800fps, were positioned directly behind the shock tube so as to capture video for use in the DIC software. The cameras were mounted in a stereoscopic orientation on two tripods and were tethered together to ensure synchronized frame capture. Various combinations of speckle pattern and discrete targets were used in this test series so as to confirm the optimal configuration of speckle and target size. Between 8 and 10 high-wattage flood lamps were used to illuminate the specimen so as to allow for low enough camera exposure times to limit the possibility of error due to significant motion blur.

AFRL utilized Correlated Solutions© DIC software to extract the history of deflection and deformed shape of the glass up to failure and through polyvinyl butyl (PVB) response (when laminated) under dynamic loading. These measurements were independently validated by comparison with the data obtained from the laser range finders.

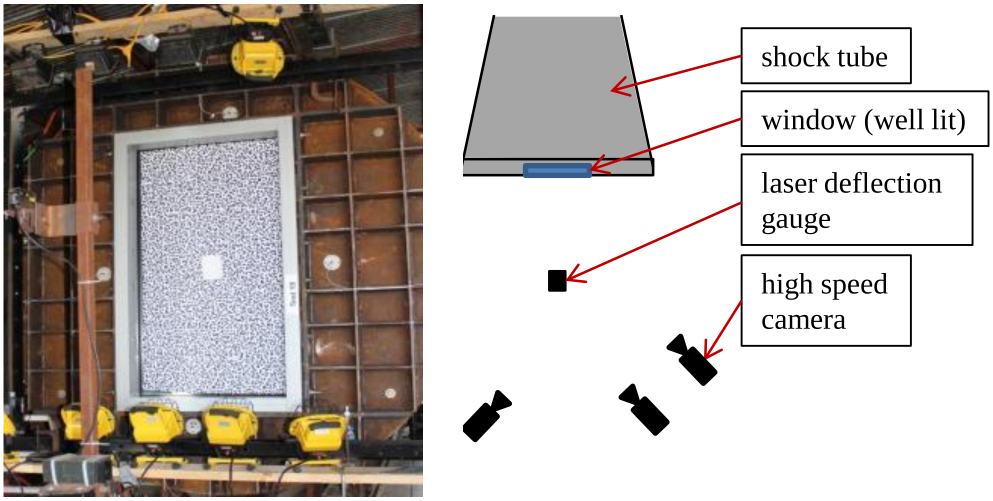

Figure 1. Shock Tube Test Setup - Instrumentation.

Blast Testing

Two full-scale blast tests were performed on twelve window assemblies (six per test) at the AFRL test facilities located on Tyndall Air Force Base in Panama City, Florida. The charge weight and standoff were selected to push the weakest assemblies near failure. The two main test variables were IGU layup and window configuration (punched-window and storefront). The day light opening (DLO) of all windows was 32.5-in × 58.5-in (0.83 m × 1.49 m). Laminated IGUs were secured to 7-in (0.18 m) deep commercially available aluminum frames with structural silicone.

Instrumentation of four of the six assemblies during each blast test included pressure gauges to measure load. Rack-and-wheel deflection gauges and DIC were used to measure the response of the mullions. Banner time-of-flight laser range finders and DIC were used measure response of the glazing, and high-speed video cameras were used to provide documentation (see **Error! Reference source not found.**).

Figure 2. Blast Test Setup - Instrumentation.

A pair of high-speed cameras (Phantom V640s, V711s, V10s), operating at greater than 1M pixel resolution and frame rates between 2.2-7.5kfps, were positioned directly behind each test bay's window assembly so as to capture video for use in DIC software. The cameras were mounted in a stereoscopic orientation within a specialized camera rig that was isolated from the surrounding test structure's response as well as the ground shock. Speckle pattern was

applied on the inward facing surfaces of the windows and mullions, and discrete targets were applied at each mullion's center and quarter points. Four 2kW halogen lamps were used to illuminate the interior of each test bay so as to allow for low enough camera exposure times to limit the possibility of error due to significant motion blur.

AFRL utilized Correlated Solutions© DIC software to extract the time history of deflection and deformed shape of the glass and mullions throughout their response under dynamic loading. These measurements were independently validated by comparison with the data obtained from the rack-and-wheel deflection gauges as well as the laser range finders.

TEST RESULTS

Overall, the shock tube and blast testing provided an abundance of data with regard to deformed shape, debris fly-out, crack propagation, glass deflection at failure, PVB bite considerations, and mullion response. This paper focuses on the analysis of data obtained from DIC. This data from the shock tube and blast tests allowed PEC to verify the deformed shape of the window during dynamic response, analyze strain (and stress) concentrations for FEA validation, and monitor frame movement during the window response.

DEFORMED SHAPE ANALYSIS

The deformed shape of the glazing and mullions is used for validation in FEA and can be used to determine the assumed load-mass factors in SDOF analysis. In the shock tube tests, only the deflection of the glazing was measured; therefore the deflection of the mullions can only be inferred based on extrapolation from glazing deflection. However, in the blast tests, the mullion response was measured and can be used to analyze the interaction between the glazing and mullions.

Glazing Response

The deformed shape of the glazing observed from the DIC during the shock tube testing shows a parabolic deformed shape after the inertial effects have been overcome early in the response as shown in **Error! Reference source not found.**. Each line represents the deformed shape at a single point in time for the horizontal cross section of the glazing at an interval of 0.153ms. Notice the flat section that exists during the initial response. The middle section of the glass is not stressed initially and responds more as a rigid body mass than a plate in flexure. However, the stress incrementally works towards the center of the window until all glass is contributing to resistance of the load through bending. At this point in time the glazing behaves according to plate theory and the deformed shape becomes roughly parabolic. This is the assumed deformed shape for the load-mass factors associated with SDOF calculations.

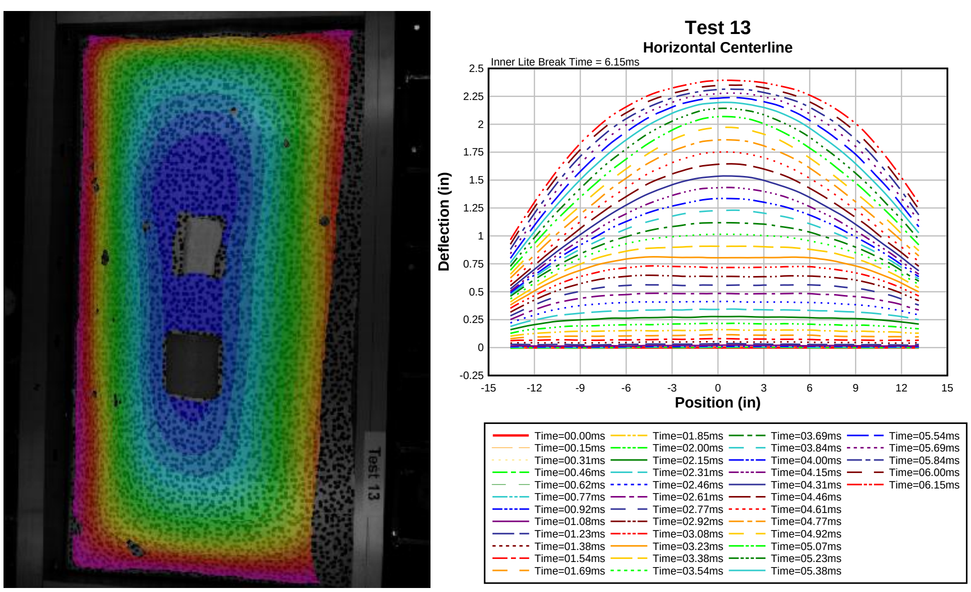

Figure 3. (left) DIC Deflection Contours overlaid on the High-Speed Video and (right) Vertical Centerline Deflection History up to Laminated Inner Lite Failure.

For the size and strength of windows tested in this program, the glazing is capable of withstanding the load long enough to transition into large displacement plate response, which explains the good pre-test predictions from SDOF analysis. With this in mind, the analysis was able to accurately predict the response of the glazing based on plate theory and the failure criteria specified through the modified Glass Failure Prediction Model (GFPM) [1]. However, for larger windows or different strength glass this may not be true. More work is needed to investigate this phenomenon.

After the glass failed, the DIC data continued to define the response of the glazing through the PVB response phase (**Error! Reference source not found.**). Notice the velocity of the top and bottom (left and right of the plot) of the glazing compared to the center of the glazing. The material in the top and bottom of the window is moving faster than the material at the center of the glass. This was also seen on tests with monolithic lites where the glass debris was monitored and tracked (**Error! Reference source not found.**). Regardless of whether the glazing is monolithic or laminated, the tests illustrated that the material that fractures first has the highest velocity after fracture.

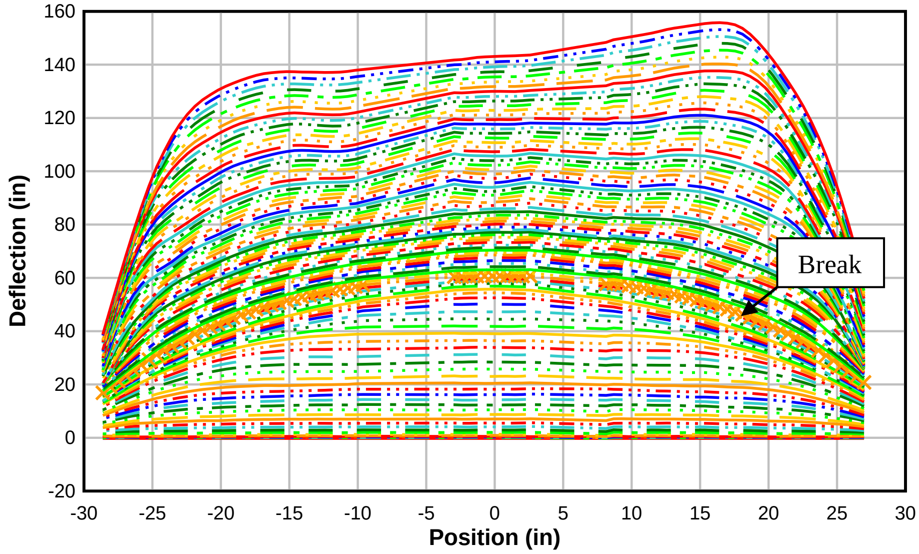

Figure 4. Shock Tube Test 13 Vertical Centerline Deflection History – Laminate.

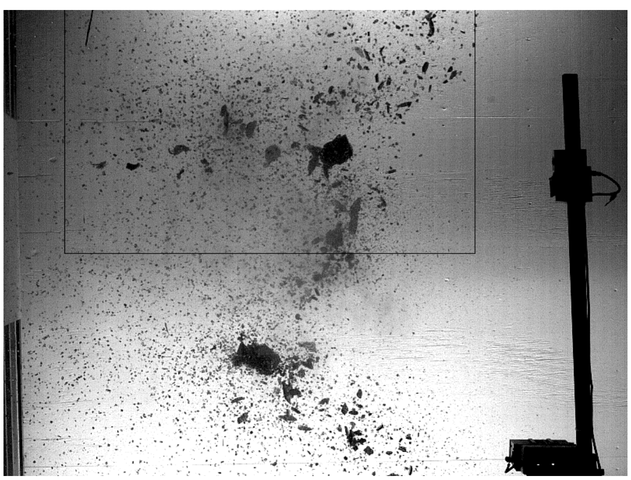

Figure 5. Monolithic Glass Debris Flyout (Shock Tube Test).

This could be due to energy release from glass fracture or elastic rebound from the unfractured glass. The glass first cracks in the corners, where the stress is the highest (discussed further in the FEA validation section). As the glass fractures, the stored energy in the glass (due to bending and tempering) is released starting in the corners (**Error! Reference source not found.**). The effects of the fracture in the corners are two-fold; the energy release propels the fractured glass and the unfractured glass as the center begins to relieve the bending stress by returning to a flat plate. This all takes place over the course of ~1ms, but this appears to be enough time for the center of the window to act as an anchor while the edges (where the cracks initiated) accelerate. If this is true, it indicates that the stress relief runs just ahead of the crack propagation. Further FEA and test data are needed to validate this assessment of the observed test data.

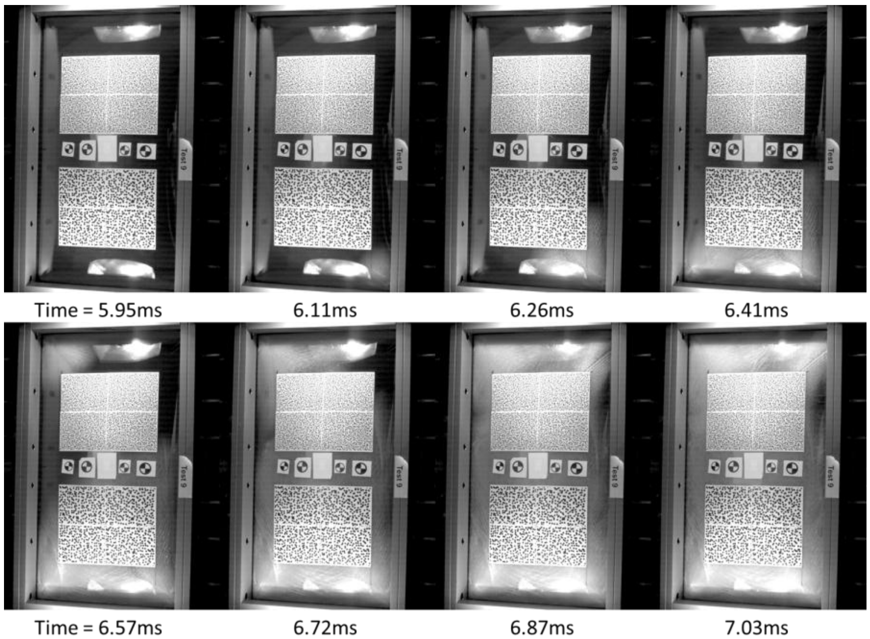

Figure 6. Crack Propagation –Laminate (Shock Tube Test 9)

If the glazing is laminated, the glass will accelerate until the PVB forms a tension membrane to further resist the load. Again, the deformed shape of the PVB in tension membrane does not occur immediately at the time of glass fracture, but forms gradually. It starts at the edges and moves towards the center (**Error! Reference source not found.**) similar to the formation of the deformed shape during the glass dominated response phase.

By differentiating the DIC data, the velocity profile of the glass debris can be analyzed. This is useful, along with debris size, in predicting shard fly out characteristics, which ultimately correspond to injury potential. Coupled with debris size and mass distribution data from the debris fly out analysis, this data was used to further calibrate debris flyout models and to link the results to injury potential [2].

STRAIN ANALYSIS AND FEA VALIDATION

DIC provides an immense amount of data on the deflected shape of the glazing measured at high-speed across the surface of the glazing. Compared to single-point deflection gages, this provides a tremendous advantage to FEA validation. Not only can the deflection at multiple points be validated, but the slope of the deflected shape and the strains can also be calculated and compared to the simulation. Figure 7 and Figure 8 show a comparison between DIC and FEA of the deflection and 1st principal stress, respectively. The stress calculation was based on Hooke's law assumptions and is thus directly proportional to the measured strain.

The fringes shown in Figure 8 are for the same point in time (at maximum deflection). Notice the good correlation on the magnitude of deflection and contour shape in Figure 7 and the stress concentrations in the corners of the glazing in Figure 8. Also, notice the difference in the amount of stress shown in the middle of the glazing. FEA gives an

accurate measurement of the stress state of the elements in this region and incorporates all sources of stress. However, DIC does not have this capability. The calculated stress measurements are taken from deflection measurements at the surface of the glass. These measurements can be manipulated into surface strains by calculating the change in distance between the points over time. The strain to stress transform is straightforward for pure bending or pure tension situations. However, as the boundary conditions on the glazing start to produce tension through the cross section, and the assumptions of pure bending begin to add the effects of tension membrane, the strain distribution is harder to identify. To estimate the strain distribution, the curvature (2^{nd} derivative of the deflection profile) was used to attempt to quantify local bending in the vertical and horizontal direction. This method shows promise, but more work is needed to further investigate the capability of measuring the strain distribution through the thickness of the glazing and accurately calculate the stress at any given point.

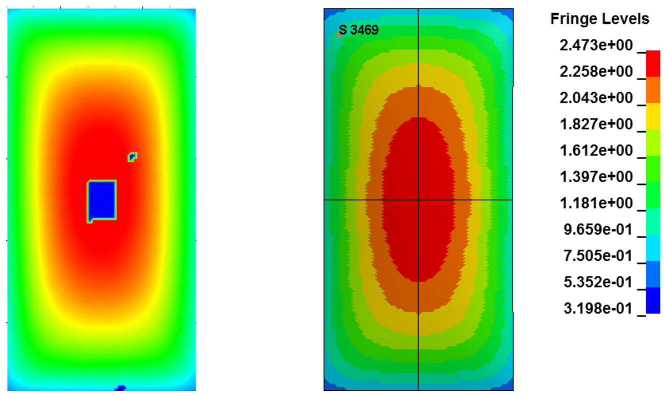

Figure 7. Deflection Comparison of (left) DIC and (right) FEA.

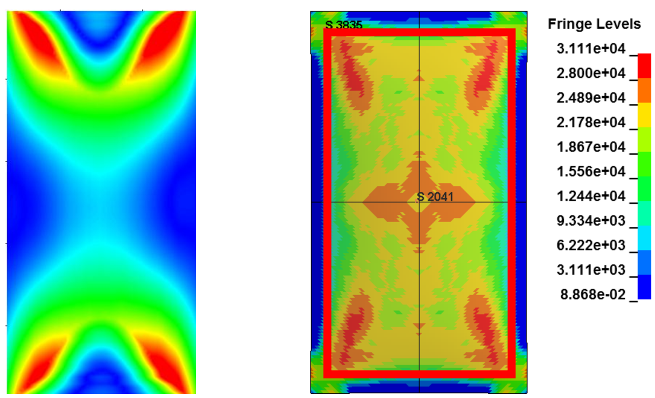

Figure 8. 1st Principal Stress Comparison at Maximum Deflection of (left) DIC and (right) FEA.

To compare the data from DIC data to FEA, a 3D software tool was written to overlay the two data sets and compare the deflections and calculated strain and stress. Figure 9 shows a snap shot of this utility.

Frame Response

The measurement of mullion response for both punched window and curtain wall configurations is needed to assess if and how much coupling occurs during the glazing response. Displacement of the mullions was not directly measured during the shock tube testing of punched windows (no speckle pattern on the mullions - Figure 1). However, by extrapolating the deflection data from the glazing response, rough estimates of frame response can be inferred. Figure 10 shows an example of the extrapolations for shock tube tests 13 and 20. The extrapolation was extended out to the extent of the vertical glazing dimensions (60-in or 1.52m) which is at vertical position equals +/- 30-in (0.76m) on the plots. The relative frame displacement in the jambs at midspan is shown by the red circles at the end of extrapolated curves (marked by thick dashed, black line. Test 13 involved a thinner laminated layup than Test 20 and the glass fractured during testing. The extrapolation was taken at the time of glass fracture which indicates nearly 0.5-in (1.27cm) of frame deformation in the head and sill mullions. The glass in Test 20 did not fracture and there-

fore shows the deflection of the glass during inbound and rebound deflection. Again, the head and sill mullions deflected about 0.5-in (1.27cm).

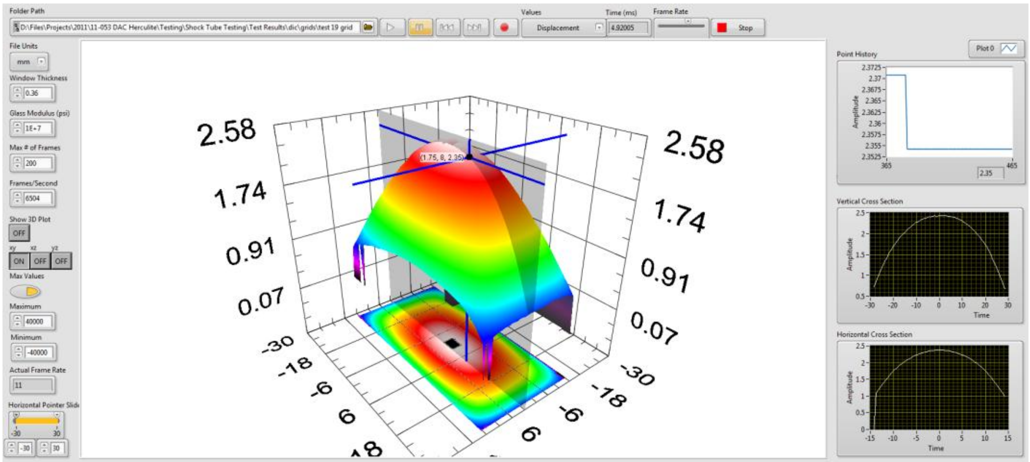

Figure 9. 3D Software Tool to Compare DIC and FEA.

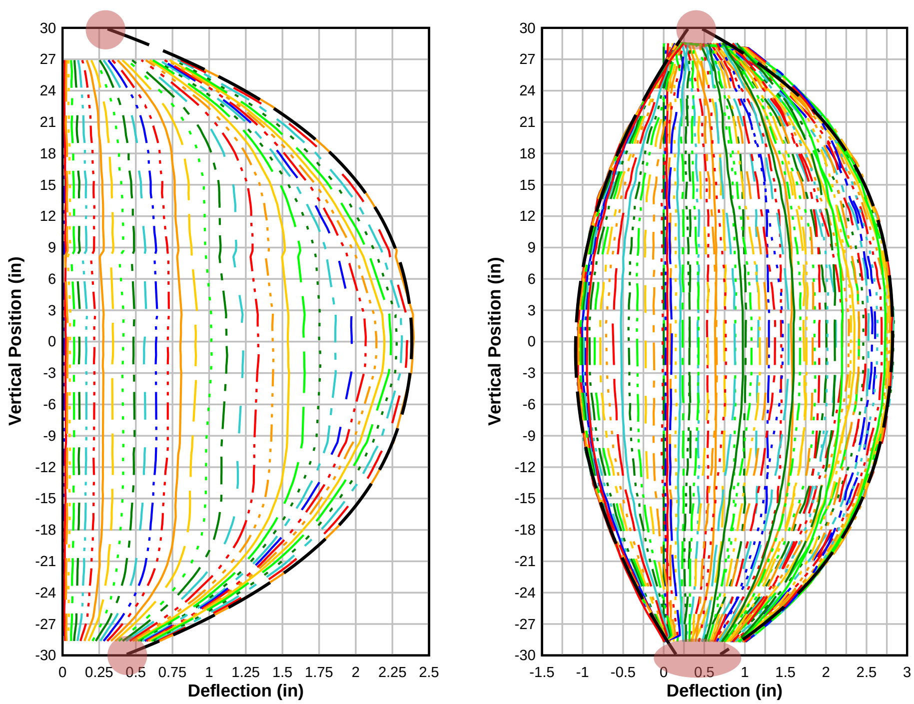

Figure 10. Glazing Deformation Extrapolation for Shock Tube (left) Test 13 and (right) Test 20. [1-in = 2.54 cm]

By combining DIC deflection data at each vertical and horizontal cross section, a reasonable measurement of the deformed shape of the mullions (head, sill and jambs) can be determined. This data was sampled through the use of the software utility depicted in Figure 9 and found to correlate well with post-test and high speed video observations.

Deflection shape data confirmed simple support conditions for the head and sill, and showed minor deflections along the length of the jambs. Since the jambs were supported continuously along the outer surface by evenly spaced bolts, these minor deflections were due to racking (local rotation) of the mullion cross section. Extrapolation of the horizontal cross section data correlated strongly with the observed state of the jambs after the tests. More work needs to

be completed to investigate the effects of this new information on the performance of the glazing and mullions for punched windows (i.e., analyzed separately or as a system).

In the blast tests, the mullions were covered with the speckle pattern and discrete markers to track the deformed shape of the mullion. However, only limited data was collected due to image resolution over such large targets. Therefore, point data was collected from the circular markers shown on the mullions in **Error! Reference source not found.**. The data collected was useful in illustrating the deformed shape through the elastic portion of the mullion response and through the formation of plastic hinges (yielding and fracture) at the midspan of the vertical mullions. Figure 11 shows the measured deflection of the glazing in a curtain wall from test 2. Notice the initial glazing deflection prior to mullion deflection at 37ms. At 43ms the mullions are deformed in a parabolic shape typical of elastic bending but at 52ms the mullion has developed a triangular deformed shape over the full height where a hinge has formed at midspan. To further demonstrate this, Figure 12 shows a curve fit through two data points (represented as red squares) of the vertical mullion deflection. During the elastic phase, the mullion exhibits a parabolic shape; then, as the plastic hinge forms, a linear curve fits better matches the data.

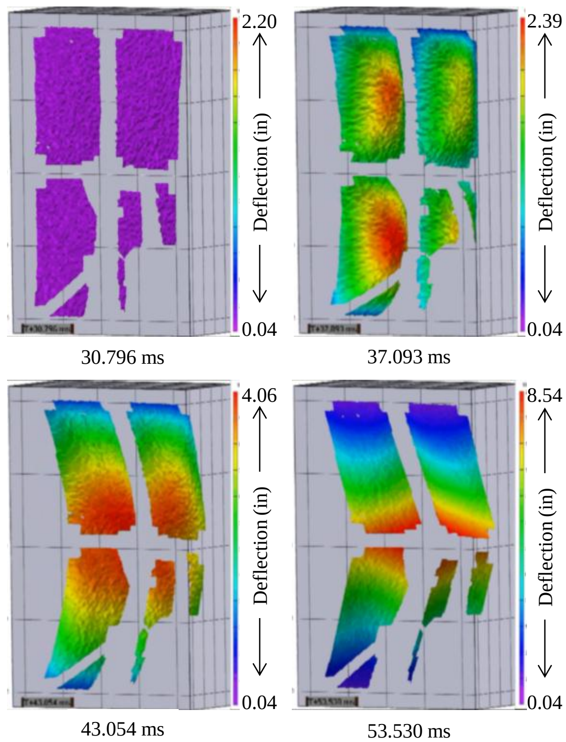

Figure 11. Blast Test 2 DIC Results: Bay 1. [1-in = 2.54 cm]

Capturing the deformed shape of the mullions permits the calculation of ductility of the mullion section just prior to hinge formation (local fracture) since the deflection can be easily measured at the time of plastic hinge formation. This is typically difficult to measure in a dynamic test, particularly for several discrete members. This data will allow further work to be completed in the validation of FEA models and for the evaluation of glazing stiffness and its impact on mullion performance.

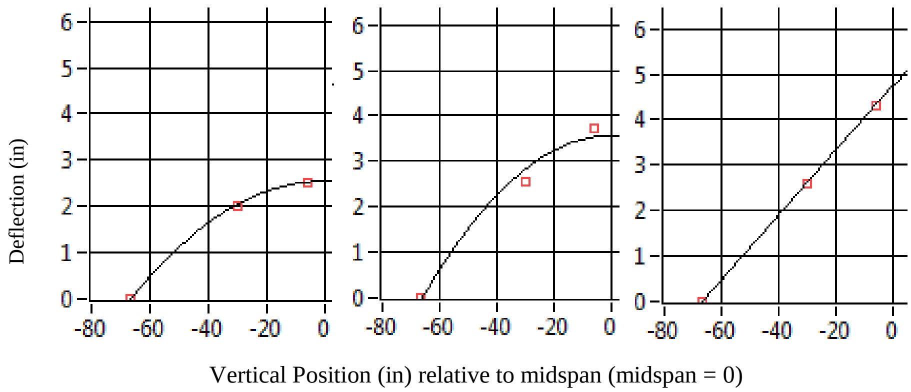

Figure 12. Transition of Deformed Shape from (left) Elastic Beam to (middle) Hinge forming to (right) Plastic Hinge. [1-in = 2.54 cm]

COUPLED VS. UNCOUPLED ANALYSIS

One of the questions surrounding SDOF analysis of storefront and curtain wall systems is the effect of coupling between the glass and mullion response. When evaluating the glass response, a common and conservative design assumption is to assume perfectly rigid supports. However, this assumption is not true if the mullion experiences significant displacement during the glass response which would allow load to be better and more efficiently distribute between glass and mullions.

For the particular combination of glazing, mullions, and loads considered in this study, it appears the coupled response has a minimal effect on the response when analyzed with a SDOF program. In blast test 1 and 2, the windows responded much faster than the mullions, which essentially decouples the two responses. Consequently, the stiff response from the Herculite® XP resulted in little dissipation of energy prior to mullion response and simple tributary area assumptions yielded good results for SDOF analysis of the mullions.

However, this may not be true for all loads and window sizes or layups. Low-pressure and high-impulse load combinations may cause the window and mullion response to be in phase and result in a coupled response. Also, larger windows will have a longer response time, which allows the flexible mullion to affect the response and vice versa. To analyze a fully coupled system, a more complicated analysis with FEA or MDOF program is required. More work should be done in this area to quantify limits for coupled and uncoupled assumptions.

CONCLUSIONS

Deformed shape assumptions for the glazing and the mullions can be measured in highly dynamic load scenarios to capture the deformed shape of the system and each component individually. The deformed shape can be used to identify the mechanics of the material during response, and can allow calculation of strain and stress distribution during elastic and plastic response, and material failure. In this particular project, shock tube and blast testing results were compared to SDOF predictions made with SBEDS-W [3]. As discussed previously, the deformed shape of the glass is consistent with large deformation plate theory and exhibits a parabolic shape soon after load is applied, and more importantly, during the time of fracture.

Blast tests also illustrated that for blast loads with high pressures the glass and mullion response was essentially uncoupled and can be conservatively designed using SDOF analysis. However, a coupled analysis may be more appropriate for more complex curtain wall systems with varying support conditions. Thus, data collected will help validate future MDOF and FEA design tools of glass and mullion systems.

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